

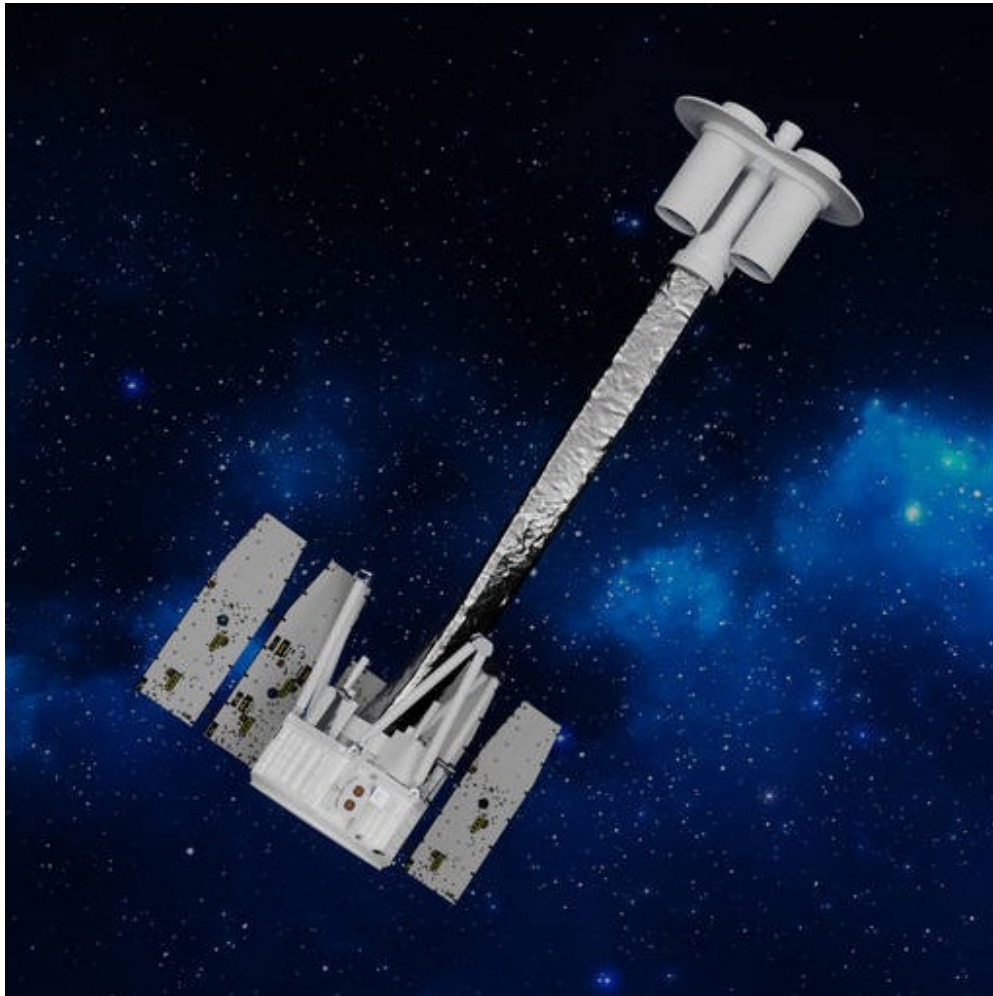
The Imaging X-ray Polarimetry Explorer (IXPE) Lessons Learned

Brian Ramsey



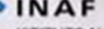









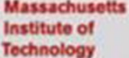
Astrophysics Branch

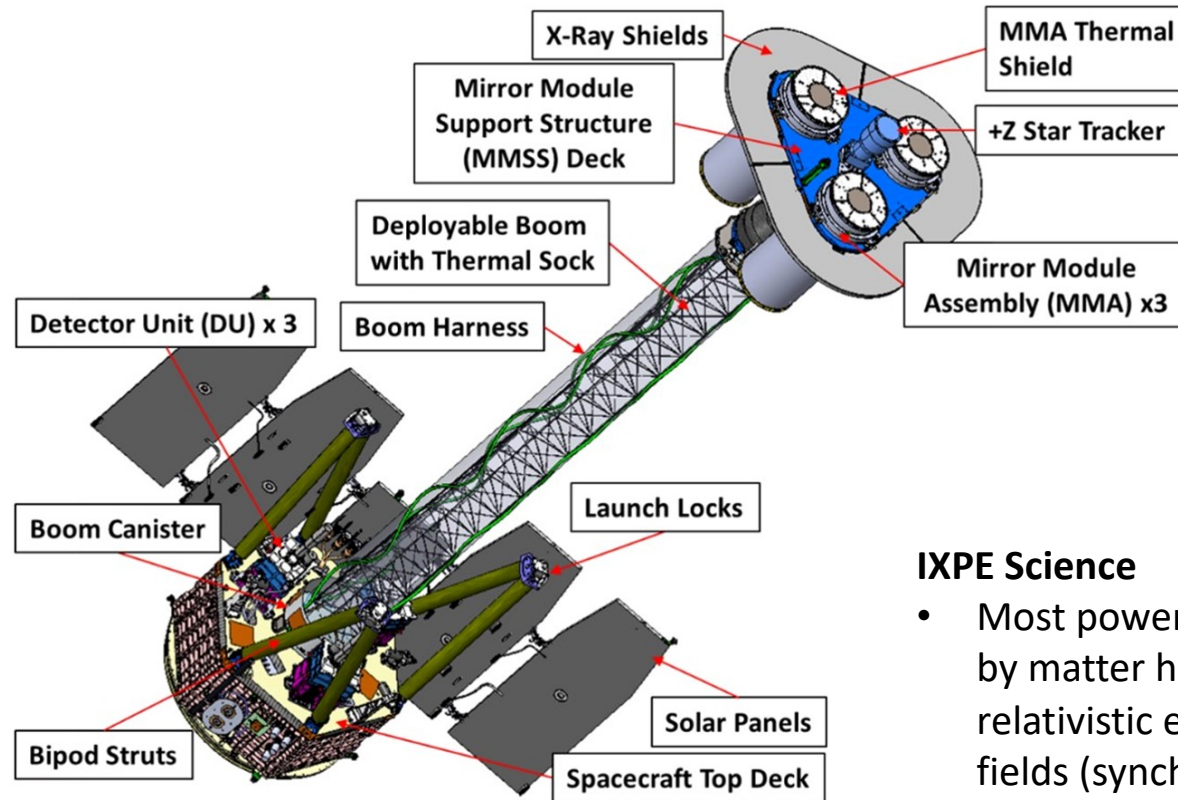
Science and Technology Office

NASA/MSFC



- Small Explorer Mission: First Observatory dedicated to X-ray Polarimetry
- Phase B started in Jan 2017
- Launched on Dec 9, 2021, ~ 1 month of commissioning
- Science operations started Jan 2022
- 2-year baseline mission, with Guest Observer phase beyond that
- SpaceX falcon 9 launch from cape into equatorial orbit
- Ground station in Malindi, Kenya.

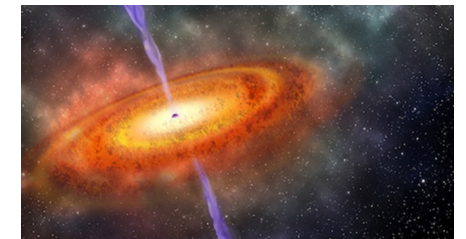
 Marshall Space Flight Center PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving	    Polarization-sensitive imaging detector systems
 Detector system funding, ground station	 Mission operations
 Spacecraft, payload structure, payload, observatory I&T	  Scientific theory
	 Thermal shields
	  Co-Investigator



- 3 identical telescopes each comprised of mirror module assembly with polarization-sensitive X-ray detector at focus
- 4-m focal length system (deployed on orbit)
- 30 arcsec HEW angular resolution
- 12.8 arcmin x 12.8 arcmin detector-limited FOV
- 5.5% polarization sensitivity for ~1 mCrab source in 10 days

IXPE Science

- Most powerful X-ray sources produce their radiation by matter heating as it spirals onto black holes or by relativistic electrons spiraling in intense magnetic fields (synchrotron radiation)
- Both these mechanisms give rise to polarization
- Polarimetry provides a powerful way of probing the emission geometry and emission mechanism in some of the most exciting cosmic sources



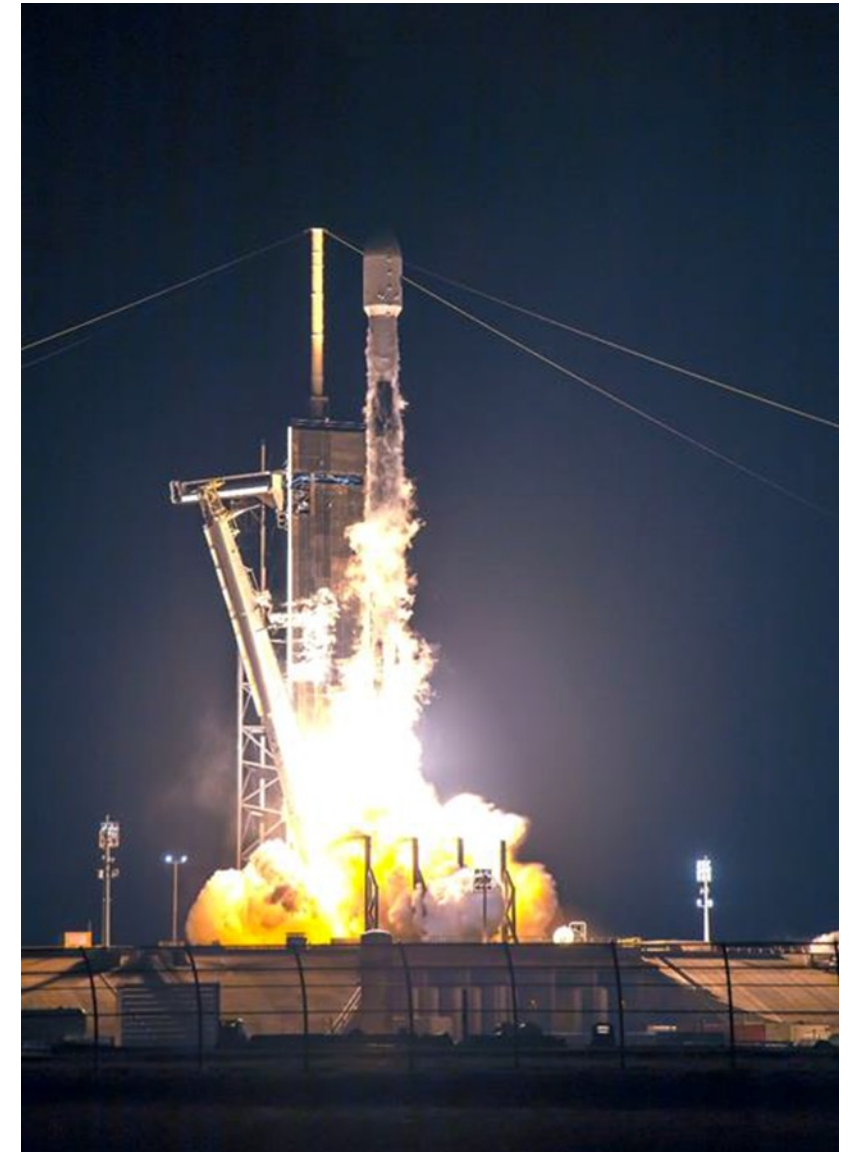
First year observing plan has 34 targets from broad range of source types. To date 40% of (26) targets have highly significant (> 5 sigma) measured levels of polarization. Observatory is working perfectly

What did I wish I had known at Phase A kickoff ?

Launch Vehicle

- It was assumed that the Pegasus rocket would be chosen for IXPE due to the equatorial orbit requirement
- Around CDR, it was announced that the launch provider would be SpaceX with a Falcon 9.
- The low-frequency sine test plus acoustic test that this entailed as well as the change of thermal environment was challenging for the IXPE observatory, particularly for environmental testing.
- We had not planned for a Cape launch (Pegasus would have been launched from Kwajalein)
 - Had to implement lightning protection after the fact on the launch vehicle.

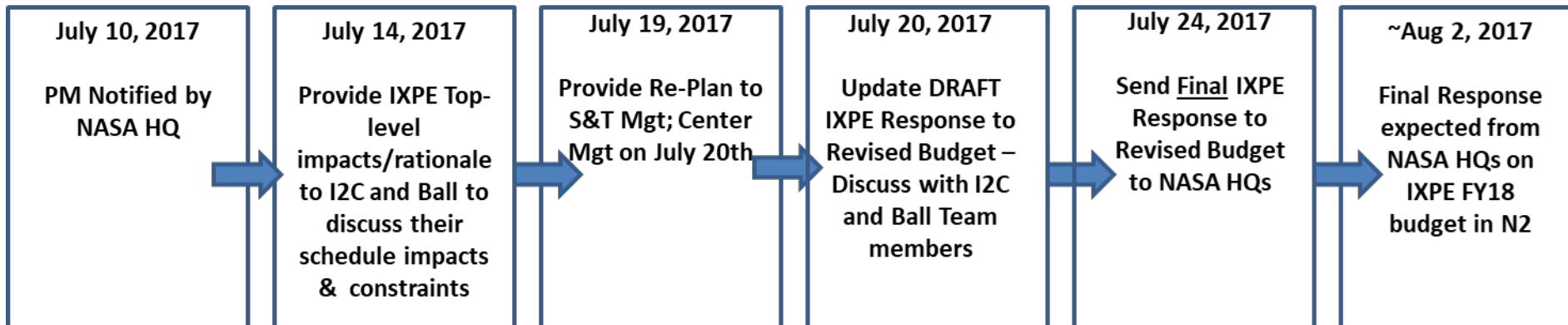
Lesson: need to have proper accounting of all possible launch vehicles and launch sites for generation of requirements



What if HQ can't supply your budget profile – replanning on fly?

FY 2018 Replan

- NASA HQ proposed a budget cut for FY18 and funding rephasing
 - Cut was \$21M, taking FY 18 budget from \$42M to \$21M, with reinstatement of \$10M in FY19
 - Requested IXP to try and maintain original PI cost cap plus inflation
 - Given 2 weeks to respond
- Replan Decision
 - Increase Phase B by 5 months and slip everything beyond by 5 months (including launch readiness date)
 - Increase funding required in FY20 (\$6.7M) and 21 (\$6.0M)
- Decision Timeline



What if HQ can't supply your budget profile – replanning on fly?

FY 2018 Replan Impacts Noted at Time

- Launch Readiness Date (LRD) slips by ~5 months
- Total PI Managed Mission Cost (PIMMC) increases from \$132.0M to \$135.8M (~\$1.7M increase due to inflation and remainder due to 5 month slip)
- Reduces Phase B (FY18 only) reserves to 15% (was 30%)
- Phase B contract with Ball Aerospace must be extended
- Instrument (I2C) schedule slightly ahead of IXPE Master Schedule
 - Increases Project Risk due to start of Instrument fabrication prior to Mission-PDR
- MMA-optics fabrication slips by ~2.5 months
 - Assumes delay in MMA-EU tests at MSFC from January 2018 to April 2018
 - Assumes MMA flight units completion slip from June 2019 to August 2019
- Delay in FY18 creates risk of losing key technical skills
 - Part-time employees facing further reduction may decide to leave for other projects

Plan agreed upon by Center, Partners and HQ ✓

Example: 2019 Replan

- Feb 2019: Government shutdown for 5 weeks. Work stopped at MSFC, but not at Ball or in Italy. Resulted in a 5-week delay of mirrors to calibration
 - Decision: perform end-to-end calibration on spare telescope only (instead of 3 flight plus spare)
 - Had extensive calibration data on detectors (Italy) and mirrors (at MSFC)
 - Needed only 1 system to show that telescope calibration can be synthesized from mirror and detector calibration data.
 - Freed up flight units immediately to ship to Ball for integration
 - Minimal risk and preserved schedule with additional margin

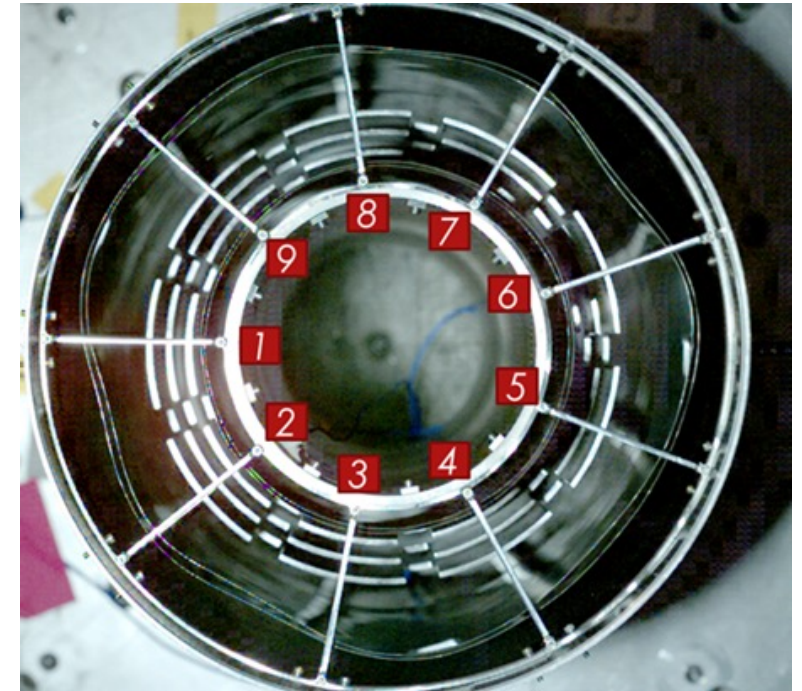
Pandemic

- This hit (March 2020) just as we were building and testing hardware. MSFC was shut down for several months, then startup packages were approved for limited access for continuing work
- Main problem for Italy and MSFC was travel to Ball Aerospace for payload integration and testing
- Worked around this by training Ball to inspect, test and integrate the Italian instrument hardware and the MSFC-provided mirror module assemblies
 - Made possible by willingness of Ball to take on this role and by flexible contracting which allowed for quick changes in scope to Ball tasks without doing a time-consuming contract modification
 - Funded a notice of change 'pool' so that new tasks could be implemented quickly
- Similar problem for X-ray end-to-end calibration (of spare flight units) , where Italy was to operate the instrument at the MSFC test facility
 - MSFC modified Italian handling and test procedures and practiced on an instrument engineering unit
 - Italian colleagues were able to participate in the calibration through the use of Teamviewer software

Lesson: negotiate flexible contracts up front that allow you to respond quickly if additional contractor support is needed (we used this many times for all sorts of unforeseen problems)

Heritage Claims

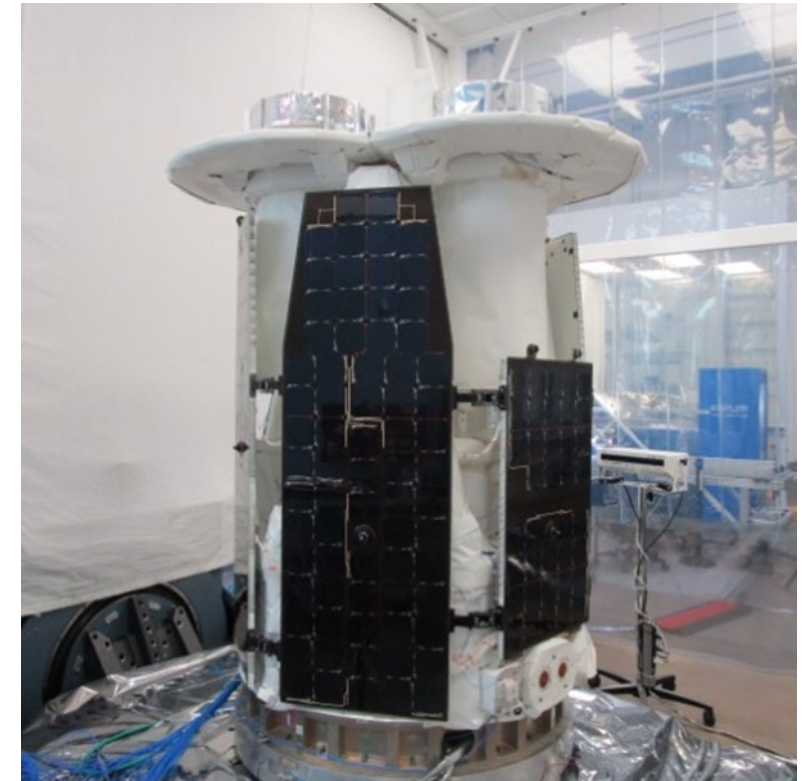
- Built many flight mirrors before, but slightly thinner shells, poor environmental controls and over-testing hardware contributed to failure when engineering unit was first tested
- Non-linear behavior of thin mirror shells
- Weakened epoxy (shows value of process development) due to high humidity in assembly room. (Same epoxy we had used extensively before). Manufacturer's data sheet gave no requirements on this
- For delicate hardware such as optics need to test at appropriate levels (MEL+3 dB) for example. Not some generic value
- Did show the great value of engineering units. Used extensively for verifying mechanical and optical design, for testing handling fixtures and procedures, ditto for calibration practice and testing, etc.



Lesson: even small changes in design can negate heritage/TRL claims. Do not over-test sensitive hardware. An engineering unit is extremely valuable.

Removal of Structural Test Model

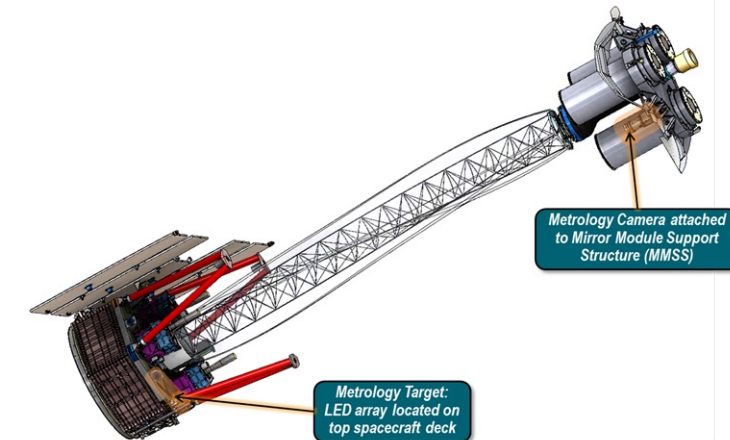
- For cost and schedule saving, we removed the structural test model that was intended to verify Observatory structures and stresses prior to integrating the payload into the observatory
- This meant that we ended up qualifying Observatory structure with all flight hardware in place
 - Due to some uncertainty in modal tests which, because of the way the Observatory was stowed, gave different modal frequencies at low Observatory input load levels than at high levels we were unsure of the loads that the delicate mirror modules were seeing
 - Had to heavily instrument the Observatory and analyze data at each step in input power to make sure MMAs were not damaged



Lesson: structural test models are very important to avoid potential damage in complex flight systems

Removal of Metrology System

- For cost and schedule saving, we removed the metrology system that was to keep track of relative motion between the two ends of the extended boom
- This decision was based on a stop analysis that showed that motions would be smaller than the angular resolution of the telescopes
- On orbit, these boom motions were found to be significantly larger
 - For bright point X-ray sources it is possible to use 'X-ray aspect' to remove this motion
 - For faint extended sources we had to develop a model of distortions vs pointing direction to remove the motion
 - Luckily this seems to work okay
- We also incorporated a tip/tilt/rotate system to reposition images if the boom deployed outside of its expected location. Fortunately, we kept that



Lesson: STOP analysis of a complex system is very difficult. Check carefully and have a backup plan !

Requirements

- Be realistic in Level-1 requirements, and do not change these
- Hold margin at lower levels to ensure level 1 requirements are met
- Think carefully about how you will verify these requirements
- Use cross-team tool for managing requirements (DOORS)

MAAR

- First full SMEX mission at MSFC did some light tailoring but the whole thing took a long time (9 months ?)
 - May not be an issue now (SMD – DMAAR) ?

Quality Assurance@MSFC

- Negotiate the appropriate level of oversight to avoid being swamped by paperwork
- What needs to be witnessed or what can be verified after the fact
 - Don't underestimate how time consuming this paperwork can be can

International Partners- Communications

- Make sure international agreements are in place to allow early exchange of technical information
- Face to face meeting are invaluable to establish good relationships and avoid mis-communication
 - Participate in on-site subsystem reviews. Often held in English

International Partners- Shipping

- Flight hardware and support equipment travelled in both directions (mainly Italy)
- Freight to Italy was not cleared by shipper. Italian representatives did that but process was very long, particularly for returning items (shipping documents had to match exactly ...leading to lengthy delays)
 - Get information on country custom processes up front
- Even very-well-packed items were sometimes damaged in shipping. Assume items will be turned on side or upside down (despite labelling). Include environment monitors inside
- Assume shipping will take a long time. Current lead time for trucks and planes can be significant

Lesson: work everything in advance. Hold face-to-face meetings when possible. Pack hardware extremely well and plan for someone on project to spend time on careful paperwork, inspections, packing, etc.

Companies come and go

The company that was to assemble the flight detectors (with decades of experience) pulled out of the project and a decision was made to do the work in-house. Their funding agencies were very skeptical about this and wanted to put more pressure on the company, but in the end the in-house approach worked very well

Lesson: be open minded to changes (despite pressure to not change original plan) and make decisions early

Expect the unexpected (also heritage)

Gas pressure slowly changed in the flight and spare detector. In retrospect the information was there in various forms since the early detector development (many years earlier) but was never attributed to a pressure change. After it was realized (during flight unit calibration) it was then possible to put forward a simple model to show that by launch it would stabilize. This caught us completely by surprise, despite ~20 years experience

Lesson: be ready to discover things you had not anticipated with hardware you think you know well

Software doesn't write itself

In the intense rush to build hardware, software can often be overlooked. It is vitally important to dedicate enough resources to the infrastructure for software development and testing. For IXPE, this was a much bigger task than was anticipated

Lesson: think carefully about software requirements and allocate appropriate resources

Concept Study

- Get outside experts to participate on red/gold teams for proposals reviews
 - Try and pick members with past explorer experience

Program

- Standing-Review-Board (SRB) members were very knowledgeable and experienced
- IXPE had a very good working relationship with the SRB, particularly the Chair
 - Called on SRB members to advise when problems arose
 - Used SRB members for subsystem reviews also

Mockups

- We built a full-size simulator of the observatory (from wood and plastic) to practice installing very thin thermal shields (1.4 micron) on the mirror module assemblies and for doing mirror inspections after the Observatory environmental testing. Given the tight packing of delicate hardware this was extremely useful for developing procedures



Transporting Observatory

- Don't take for granted that environmentally-controlled means what you think it does

Mascot

- Choose wisely. We had a goat that worked exceptionally well for all integration and testing





GOOD LUCK !